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The Processes of Aggradation and Incision in the Channels in the Terek River Basin, the North Caucasus: The Hydrological Fluvial Archives of the Recent Past

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Abstract: The rates of incision and aggradation in the channels in the Terek River basin (North Caucasus) for the last 50–85 years were estimated at 18 gauging stations. The stage–discharge method (annual low water stages at the same discharges) was applied. The stability of the Terek River channel was recorded on the tectonically subsiding Tersko–Kuma Lowland. On the subsiding Kabardian Plain, channel aggradation up to 14 mm a^{-1} was registered. The rapid (~32 mm a^{-1}) incision of the Terek River occurs within the antecedent valley of the rising Sunzha Ridge, causing regressive erosion and incision (~25 mm a^{-1}) of rivers on the Ossetian Plain, despite its tectonic subsiding. The rivers in the uplifting mountains of the North Caucasus transport the sediments delivered from slopes as climatically controlled debris flows. Aggradation and incision here alternate without a visible overall trend. The rates of modern channel bed deformations are 10 to 100 times higher than the mean rates of tectonic movements. The main effect of tectonics is the changes in river channel slopes, which cause changes in the bed load transport budget and channel bed deformation. Human-made constructions induce rapid deformations in the channels but have a local effect.

Keywords: North Caucasus; river channels; gauging stations; time series; low water stages; channel bed deformations; tectonic processes

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1. Introduction

The incision and aggradation of river channels over long periods (often called "deformations" in fluvial hydraulics papers [1]) are usually studied using geological and geomorphological methods, beginning with classical papers [2,3]. Numerous investigations of fluvial archives, i.e., the texture and structure of alluvial deposits and river channels morphology, have allowed us to estimate the rates of river channel incision or aggradation using the relative heights of dated terraces or the thicknesses of alluvium accumulations. Usually, fluvial processes were averaged over periods of thousands of years and more in different environments, from high mountains [4,5] to hills and plains [6–10] (see also bibliography in [11]). Rarely, in the case of catastrophic river incision rates, such methods have been applicable for the last hundreds of years and decades [12–14]. At the same time, there are other available fluvial archives of another type: the hydrological data on discharges and water levels at gauging stations. These archives on paper or in digital form make it possible to estimate with high accuracy the magnitude and rate of long-term changes of water stages and channel bed deformations of river channels in the recent past [15,16] brought about both by human activity and natural causes. Probably, Herodotus [17] described the first example of the application of the fluvial archive of this type to estimate the rate of the vertical growth of natural levees of the Nile River. He wrote: ". . . in the reign of king Moiris, whenever the river reached a height of at least eight cubits it watered Egypt below Memphis; and not yet nine hundred years had gone by since the death of Moiris, when I heard these things from the priests: now however, unless the river rises to sixteen cubits, or fifteen at the least, it does not go over the land." Toussoun [18] described historical and archaeological investigations of water levels of the Nile River (using so-called nilometers), including the interesting record of significant changes in the water level over time at Luxor. This information was used by Biswas [19] to estimate the river bed aggradation, who quoted "a rise of the river bed of 2.68 m (8.8 ft.) in 2800 years, or at the rate of 0.096 m (3.8 in.) per century". The example of the Nile River's hydrological history is unique. Usually, fluvial archives of this type are used to investigate much shorter channel bed deformations (over decades) such as a rapid aggradation in the Waipoa River in New Zealand over a period of 50 years [20] or the Terek River delta formation during the last 100 years [20,21].

In the proposed article, the channel bed deformations of the river channels in the Terek River basin upstream from the Terek delta are analysed based on the hydrometric data for periods of up to 85 years. The velocities and signs of these channel bed deformations are compared to the climatic trends, velocities and signs of tectonic movements in the tectonically active region of the North Caucasus and to the effects of the constructions of various types in the channels.

2. Geographical and Geological Setting

2.1. The Physiography of the Terek River Basin

The basin area of the Terek River is 43,200 km^2, the length of the river is 623 km and the average annual water discharge at the head of the delta is 291 m^3 s^{-1} (the mean for 1924–1988). The upper reaches of the Terek River and its main tributaries are located within the main range of the North Caucasus Mountains with the summit of the Kazbek Mountain (Figure 1). The mountainous part of the basin occupies about 5300 km^2. In this region, the main river and its tributaries cross several mountain ranges and intermountain basins. The next region, moving from the south to the north, is the sloped Ossetian Plain, at the lower part of which, near the Sunzha Ridge, most of the tributaries converge into one channel of the Terek River. The Terek River crosses the Sunzha Ridge through the Elkhotovo Gates and flows into the Kabardian Plain. The total area of these two plains is ~4000 km^2. Further, the Terek River crosses the Terskiy Ridge and in the upper part of the Tersko–Kuma Lowland, its large tributary, the Malka River, flows into it. At this point, the Terek River turns east and flows through the Tersko–Kuma Lowland.

2.2. The Geological Structure

The physiographic regions described above differ in their tectonic and geological structure. Following the classical work of Milanovskiy [22], with the addition of a recent geological survey [23], we shall use the main chronological boundary at the Akchagylian time, about 3.4 million years ago, when the North Caucasus was eroded to become a hilly country. From that time, this erosion surface was raised by tectonic uplift to the height of 2.5–3 km with a mean rate of about 0.7–0.9 mm a^{-1}, forming the ranges of the Caucasus Mountains (Figure 2). This surface was fractured by deep tectonic faults; therefore, the different blocks raised at different rates. The channels of the Terek River and its tributaries were incised by up to 1.0–2.0 km into various rocks, which compose these mountains. The temporally mean and spatially maximum rates of incision were 0.3–0.6 mm a^{-1}. To the north, the tectonic uplift is inversed to subsidence. There, several basins filled with deposits of various ages were formed. The thickness of sediments younger than the Akchagylian is up to 1.5 km. Therefore, the mean rate of subsidence is estimated at ~0.4 mm a^{-1}. These basins, divided by anticlines of Sunzha and Terskiy Ridges, correspond to the Ossetian and Kabardian Plains. The uplift of these ridges began at the end of the Pliocene; the estimated uplift rate is 0.2–0.3 mm a^{-1}. The Tersko–Kuma Lowland follows the deepest synclinorium with the thickness of deposits younger than the Akchagylian over 1.5 km.

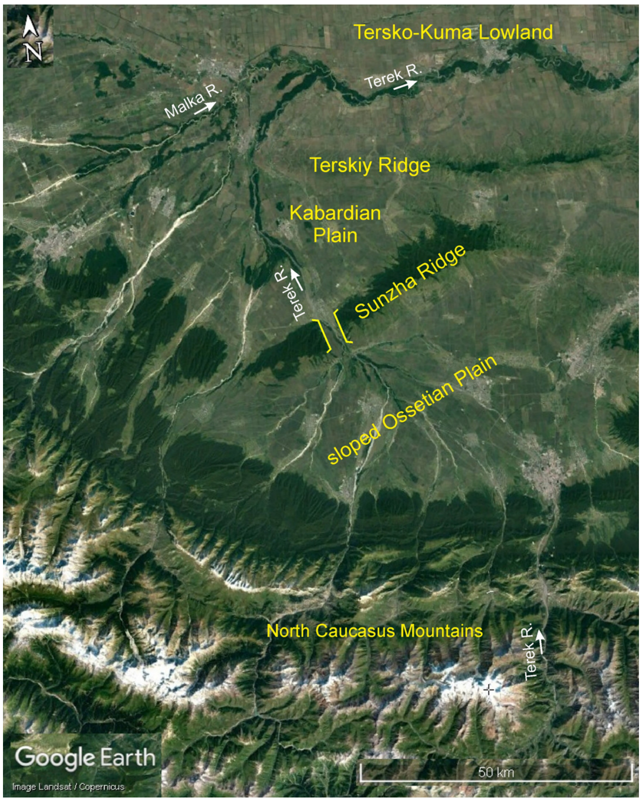

Figure 1. Space image with main physiographic regions in the Terek River basin (the North Caucasus). The cross shows the position of Kazbek Mountain, the figure of the gates—the position of Elkhotovo Gates in the Sunzha Ridge.

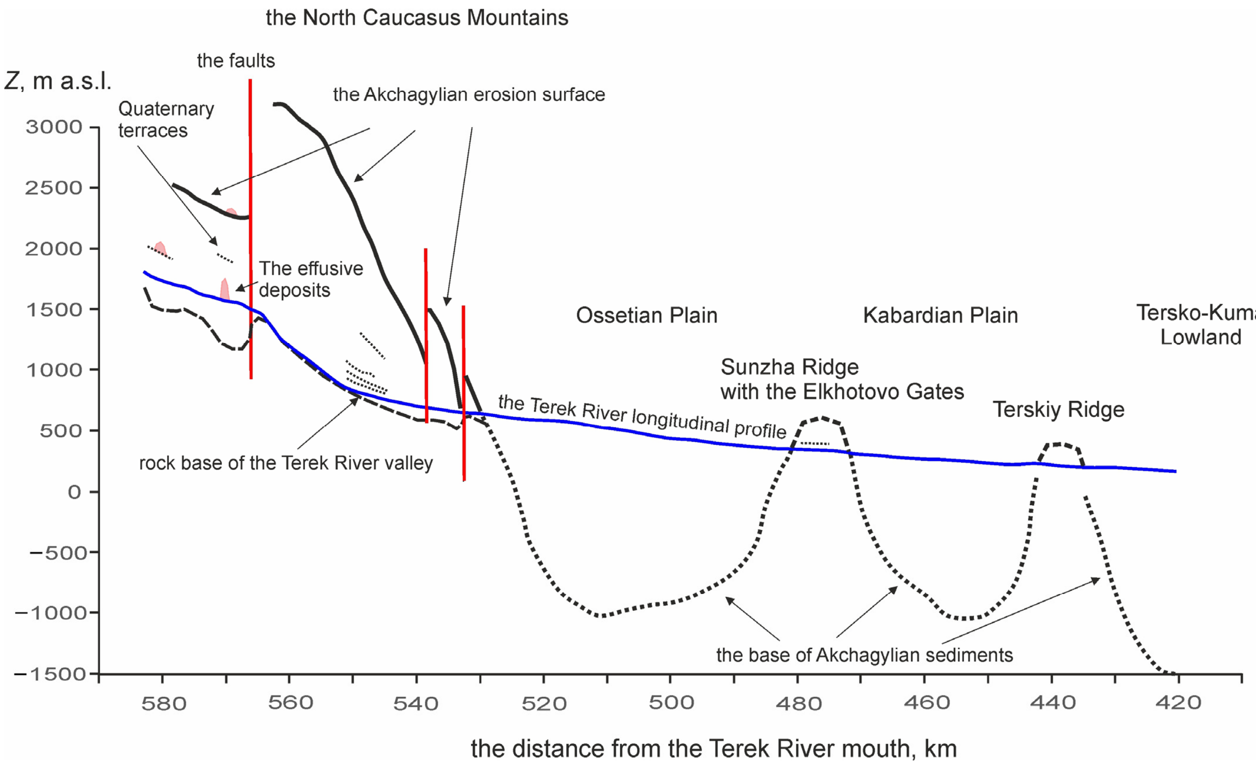

Figure 2. The morphology of the Akchagyl erosion surface/the base of Akchagyl deposits along the main river (generalised from Milanovskiy [22]), showing the intensity of tectonic tendencies—uplift and subsidence.

3. Materials and Methods

Along the Terek River and its tributaries in the mountainous, foothill and lowland parts of its basin, there are 18 main hydrological stations with long periods (up to 85 years) of observations of water levels and discharges (Figure 3, Table 1). These materials published in printed hydrological yearbooks since 1936 [24] and digitally on the website after 2008 [25] were used in further analysis. These hydrological data allow the reconstruction of the processes of aggradation and incision in the channels in the Terek River basin that occurred in the recent past.

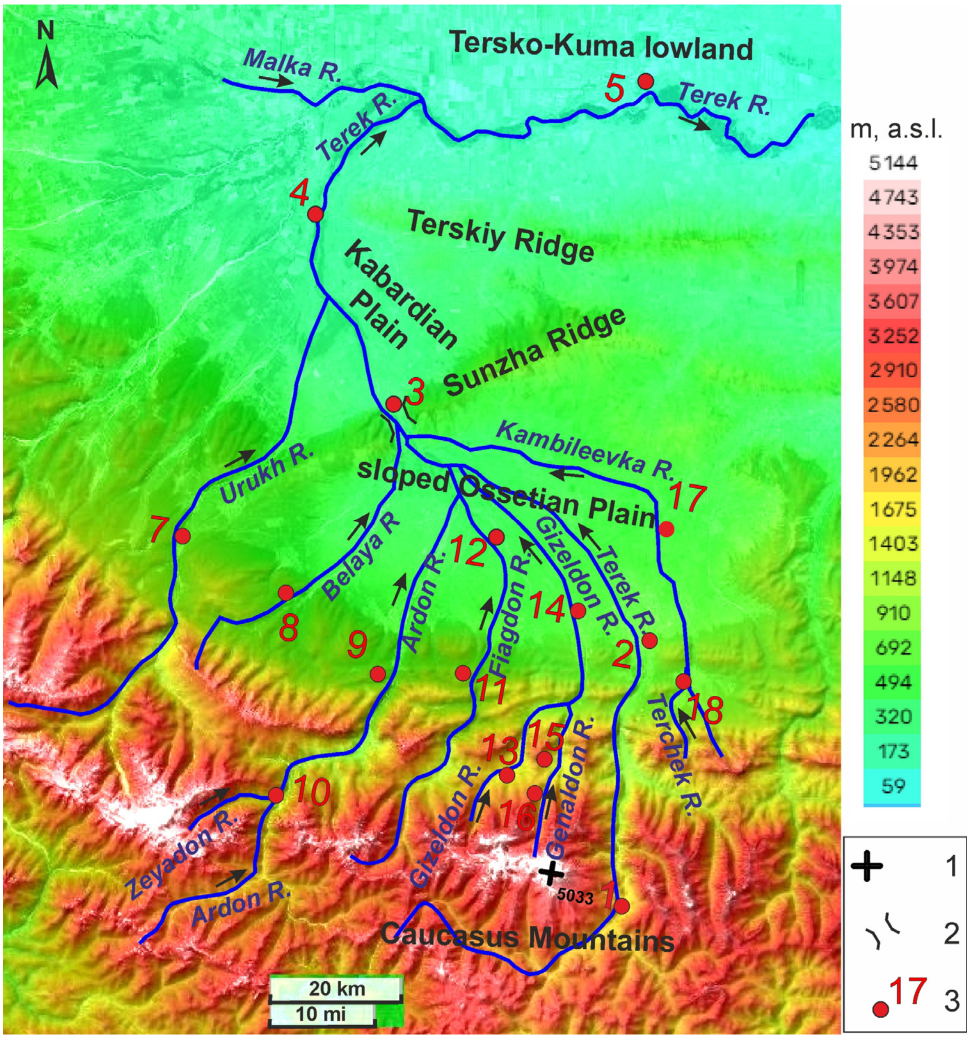

Figure 3. The main physiographic regions and the river net in the Terek River basin (the North Caucasus). 1—the position of Kazbek Mountain; 2—the position of Elkhotovo Gates in the Sunzha Ridge; 3—the positions and numbers of gauging stations. The names of these stations according to their numbers can be seen in Table 1. The cartographic background from free topographic maps can be found at https://en-us.topographic-map.com (accessed on 17 June 2023).

There are several ways to estimate channel bed deformations of the river channels that are used in hydrological practice. The first method that can be used for this purpose consists of taking repeated measurements of the channel bed altitudes at the cross-sections. The channel geometry in the cross-sections along the river is often investigated for projects relating to water resource management, such as channel capacity calculations [26] and irrigation system construction [27]. In the rapidly deforming channels, such works are conducted repeatedly to monitor the changes in channel morphology. For example, the rapid deposition in the Waipoa River in New Zealand was determined by taking repeated measurements of cross-sections 3 times over 50 years [20]. The channel geometry of the Terek River in the delta was measured 6 times within the period 1976–1987 in 27 fixed cross-sections in the 46-km-long stretch. A rapid channel incision due to the artificial straightening and channel aggradation due to the Caspian Sea level rise were investigated [21]. Usually, the data about river channel cross-section morphology are not publicly available and are deposited in a project department archive.

Table 1. The information on the gauging stations used for the analysis of the channel bed deformations of the river channels in the Terek River basin. Positions of the stations and their numbers are shown in Figure 3.

The River Name/Main River	The Number in Figure 3	Gauging Station	Distance from the Mouth of the Terek River, km	Basin Area F km^2	Annual Discharge Q $m^3\ s^{-1}$	Annual Suspended Sediment Transport Rate R $kg\ s^{-1}$
Terek	1	Kazbegi	575	778	23.8	29
	2	Vladikavkaz	530	1490	35.2	62
	3	Elkhotovo	472	6490	105	77
	4	Kotlyarevskaya	437	8920	131	130
	5	Mozdok	359	20,600	224	300
	6	Chervlenaya	192	23,100	–	–
Urukh/Terek	7	Khaznidon	495	1150	24.2	22
Belaya/Terek	8	Kora Ursdon	509	304	6.48	2.5
Ardon/Terek	9	Tamisk	525	1080	29.2	23
Zeyadon/Ardon	10	Buron	553.3	100	4.03	_
Fiagdon/Ardon	11	Tagardon	525	410	7.13	_
	12	Michurino	501	474	5.1	_
Gizeldon/Ardon	13	Dargavs	553.2	129	2.75	2.3
	14	Gisel	521.2	410	8	_
Genaldon /Gizeldon	15	Tmenikau	551.2	55.9	2.73	8.3
	16	Karmadon	547.2	70	2.8	_
Kambileevka /Terek	17	Olginskoe	541	359	3.15	1.6
Terchek /Kambileevka	18	Tarskoye	565	77	1.8	_

The other type of hydrological information that can be potentially used for the estimation of channel bed deformations is discharge measurements at the gauging stations of large rivers. These measurements do not provide a spatial distribution of channel deformations but show temporal changes in the river channel bed at a given cross-section. The results of each discharge measurement at a given gauging station are usually presented in the tables including water stage, discharge, channel width, maximum depth, mean depth and, in some cases, slope and suspended sediment concentration as well as the information about the method and the accuracy of the measurements. This information is deposited in the archives of the national hydrological departments and is usually publicly available by order but in some cases is published [24].

The most common public information, available from national websites (for example [28]), are the time series of daily stage and daily discharge. The relationships between measured discharges Q and water stages H ($Q(H)$ curves) are unstable in time under conditions of significant deformation of river channel beds, which is especially typical for mountain rivers. This instability of stage–flow curves makes it possible to estimate the magnitude of channel bed deformations. For this purpose, the relationships between discharge and stage are constructed for different years and the difference in water levels at the same discharge is used to evaluate changes in the channel bed elevation.

This method was used to estimate the deformations of the channel beds of the lowland rivers in China [16] and Russia [29] and of Subcarpathian rivers in Romanian [15] river channels and is included in the handbook on fluvial processes [30]. This is the main method used in the current paper.

The fact that the variability of water stages, H, at the same flow rates, Q, reflects the channel bed deformation follows from the equation of motion:

$$H = Z_{min} + D_{max} = Z_{min} + kD_{mean} = Z_{min} + k\left(\frac{nQ}{W\sqrt{S_*}}\right)^{3/5} \quad (1)$$

Here, Z_{min} is the channel bed minimum altitude, D_{max} is the maximum depth at the same point, D_{mean} is the channel mean depth, W is the channel width and n is the Manning roughness coefficient. The coefficient k is a channel shape factor, equal to 1 for a rectangular, 1.4 for a parabolic and 2 for a triangular channel. Equivalent slope, S^*, includes the corrections to the slope of the free surface, S, due to the change in the flow velocity, U, along the length, x, in time, t:

$$S_* = S - \frac{\partial U^2}{2g\partial x} - \frac{\partial U}{g\partial t} \quad (2)$$

Here, g is the acceleration due to gravity.

Variables n, W, S and U are generally related to discharge and are assumed constants for the same discharges.

The accuracy of the stage–flow curve method mostly depends on the effects of nonuniform motion (Equation (2)) and the temporal changes in the shape of the channel cross-section (shape factor k in Equation (1)).

The effects of nonuniform motion on the correlation between the water stages, H, and channel bed altitude, Z_{min}, are different in the stretches of acceleration or deceleration of the flow and vary depending on the position of the measurement site relative to the moving elements of channel relief. In stretches of flow deceleration, the equivalent slope, S*, increases and the flow depth decreases compared to uniform flow conditions. In stretches of flow acceleration, the situation is the opposite. On the rivers of the North Caucasus, the maximum differences in depth with nonuniform flow can be about ±10% relative to the depth with a uniform flow in low water conditions.

More significant is the variability in the maximum flow depth due to the change in the shape of the channel cross-section caused by the movement of riffle–pool pairs. The effect of channel shape change can be considerable and the water stage at the same discharge will vary due to this effect.

The variability of the factors influencing the depth of the flow (the difference between the water stages, H, and channel bed altitude, Z_{min}), in Equations (1) and (2) is minimal when choosing stages at the same discharges in an ice-free low water period on the same branch of the hydrograph. Therefore, the difference in water stages in different years under the same conditions shows channel bed deformations of the river channels within the intervals averaged for the periods longer than the period of the riffle–pool wave. These deformations are further represented as a time series of annual low water stages (ALWS) for low water discharges (one data point per year).

In the conditions of relatively stable river runoff, the change in the minimal stage for the low water period or even stages of certain durations calculated for different decades [31] can be used to define the channel bed deformations of the river channel. This information is less accurate but can be useful for gauging stations without discharge measurements.

The time series of annual low water stages for low water discharges were composed of 18 gauging stations along the Terek River and its tributaries. The dates of measurements were selected within ice-free periods, usually in March or in October–November. Since it was not possible to find equal daily water discharges in all years, the stages were recalculated to the same discharge based on the relationships between water stages, H, and discharges, Q. In addition to such minor corrections, changes in gauge zero, which are recorded in hydrological yearbooks, were also taken into account. These time series ALWS are assumed equal to the changes in the elevations of the river channel bed.

4. Results

4.1. The Main Factors of the Channel Bed Deformations

4.1.1. The Main River Longitudinal Profile

The longitudinal profile of the main river—Terek—is the most typical, as the river crosses all physiographic regions (Figure 4A). Its general shape within the stretch upstream from 470 km from the mouth is concave and stepped, with an increase in slopes when crossing mountain ranges and a decrease in intermountain basins. The main step is in the Dariali Gorge (550–565 km from the river mouth). Here, the slope of ~20 m km^{-1} in the Koban basin increases to ~70 m/km in the gorge and then decreases to ~10–15 m km^{-1} in the Chmi basin.

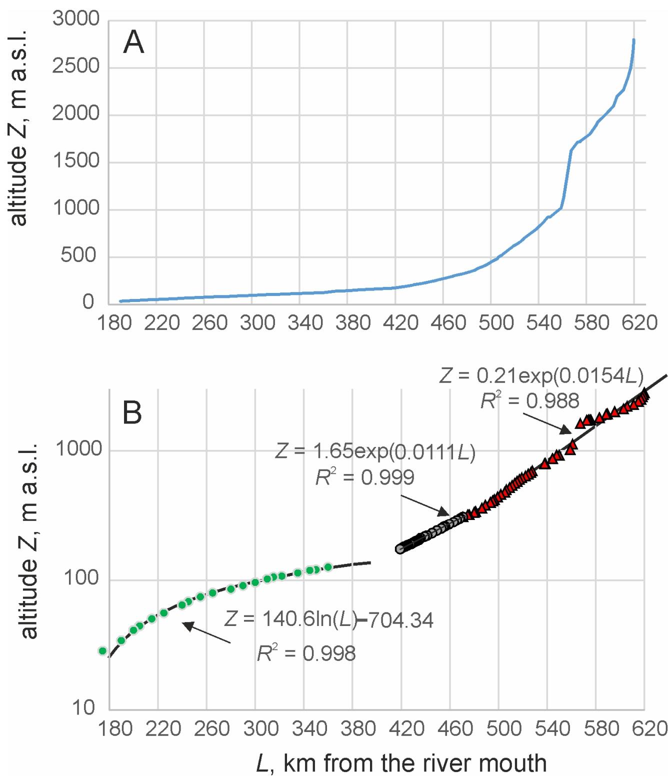

Figure 4. The longitudinal profile of the Terek River. See the text for explanations.

In the section 470–420 km from the mouth, the concave shape of the longitudinal profile is preserved but the profile is less inclined. The shape of the longitudinal profile changes to slightly convex below the Terskiy Ridge in the Tersko–Kuma lowland; this convexity is better regarded in the figure with the logarithmic vertical scale (Figure 4B).

4.1.2. The Bed Alluvium Grain Size

The distribution of the grain size of the channel alluvium along the Terek River is based on the information from the Hydrological Survey [24] and the field research conducted by the author and his colleagues [32]. There are three sections of the river channel with different types of longitudinal change in the mean diameter of channel alluvium particles (Figure 5).

In the mountains, channel alluvium consists mostly of cobbles and boulders, with a predominance of cobbles in the intermountain basins and boulders in the gorges crossing mountain ranges (red triangles in Figure 4). The mean diameter of the bed channel alluvium changes accordingly to the relief, with the maximum in the Dariali Gorge where the channel bed slope reaches its maximum.

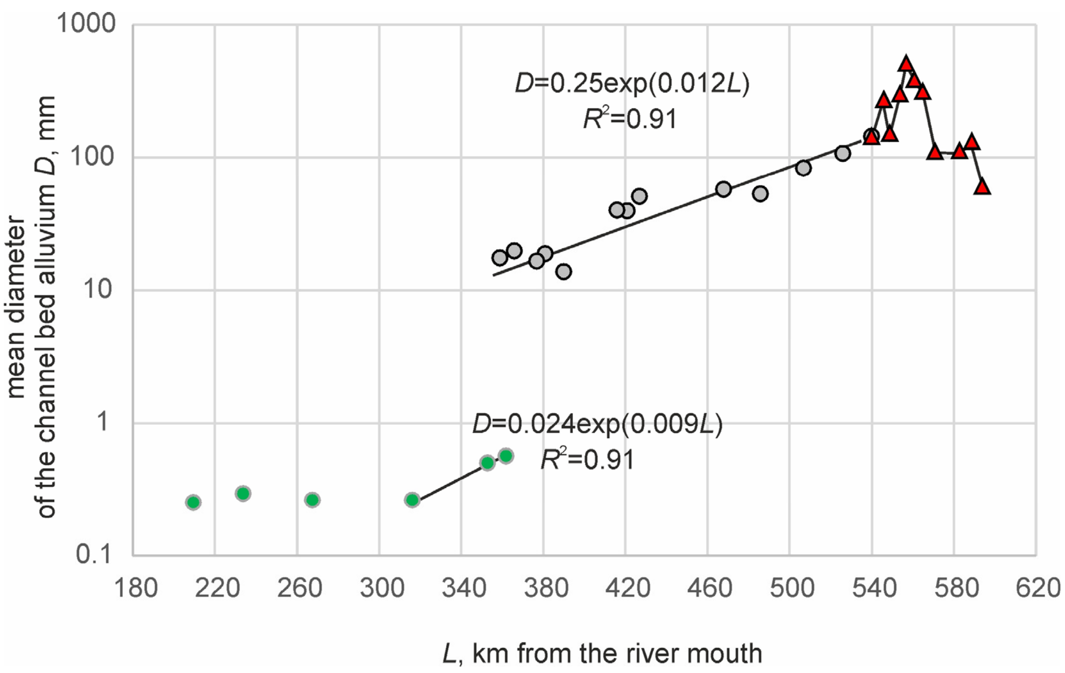

Figure 5. The distribution of the mean diameter, *D*, of channel alluvium along the Terek River. See explanations in the text.

Boulders do not move below 540 km from the river mouth, where the channel slope is less than 13 m km^{-1}. Downstream, in the Ossetian and Kabardian Plains, the mean diameter of the bed alluvium decreases from 100–140 to 40 mm, mostly due to a decrease in cobble content from 80 to 15% (grey circles in Figure 5). A small increase in the mean diameter (to 57 mm) and in the content of cobble (to 35%) is observed at the Sunzha Ridge, following a slight increase in the channel bed slope.

Down the river from the Terskiy Ridge, within the first 60 km of the Tersko–Kuma Lowland, the mean diameter of the bed alluvium decreases to 18–20 mm in natural conditions. At this reach, the histogram of the alluvium size is bimodal, with the maximum being in pebbles and in sand, and the minimum content of the particles of a very fine gravel class. The movement of the gravel–size particles stops at ~359 km from the river mouth, where the channel bed slope decreases to 0.6–0.9 m km^{-1}. The histogram of the alluvium size there again becomes unimodal and the mean diameter of the bed alluvium decreases by one to two orders of magnitude, from pebbles to sand (green circles in Figure 5). Down the river, the bed alluvium is sand and its size does not change significantly (Figure 5). The channel bed slope is within the range of 0.3–0.6 m km^{-1}.

4.1.3. Climate and Water Flow

The climate of the North Caucasus [33] is quite diverse: hot and arid on the plains and in the foothills and cool and humid in the mountains. The average temperature in January in the foothills is −4–−5 °C. The average July temperature here is 18–22 °C; during the warm period (May–September), 300–600 mm of precipitation falls.

The annual amount of precipitation in the mountains reaches 900–1000 mm, decreasing in the intermountain basins to 300–400 mm. The maximum precipitation occurs in summer. The temperature in January is −7–−9 °C. Summer in the mountains is short, cold, overcast and rainy. The air temperature decreases with altitude by 0.5° per 100 m and in July, at an altitude of 2–3 km, it is less than 12 °C.

The temporal variations of the mean month and mean annual air temperatures at the Vladikavkaz station are typical for the whole North Caucasus and Terek basin in particular [33] and show a distinct increase through time. The positive trend, estimated from a cubic approximation of the initial time series by the least square method, was

0.01° per year for the period 1939–1990 and 0.07° per year after 1990 (Figure 6A). The Mann–Kendall test confirms the overall positive trend (Z_S = 3.5, Z_{s_cr} = 1.96).

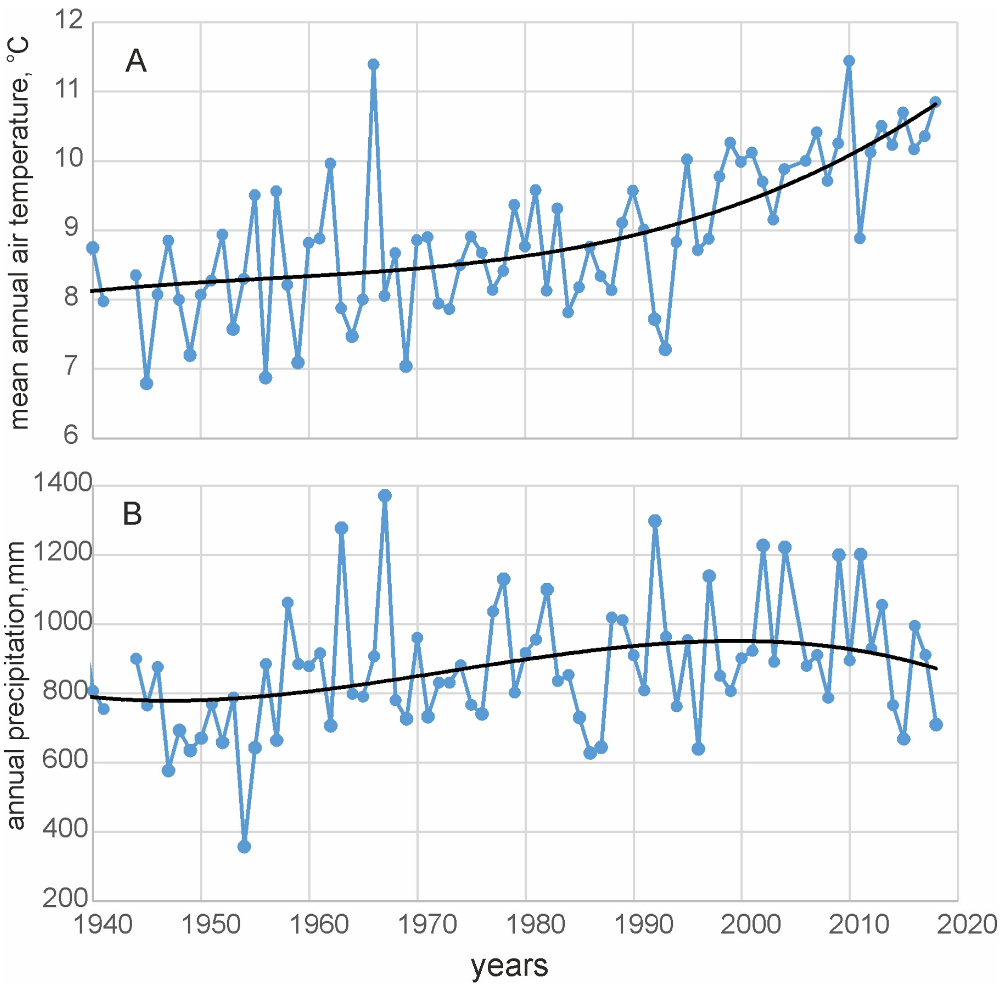

Figure 6. Temporal variation in mean annual air temperature in °C (**A**) and annual precipitation (**B**) at the Vladikavkaz station with cubic polynomial approximation in black lines.

The precipitation at the Vladikavkaz station also increased during the years 1939–1990 by 2.94 mm per year; afterwards, the sign of the trend changed and precipitation decreased by 1.7 mm per year (Figure 6B). The Mann–Kendall test does not fix the statistically significant trend neither for the first (Z_S = 1.74, Z_{s_cr} = 1.96) nor for the second period (Z_S= −0.26, Z_{s_cr} = 1.96).

The fluvial processes are most intensive during floods. There are several floods each year during the summer (June–September) at the Terek River basin and mean discharges for these months are well correlated with the mean annual discharge (R^2 not less than 0.85). Therefore, the mean annual discharge is used further (due to convenience of availability) to illustrate runoff temporal variations. The temporal variations of the water flow are different for the basins of different rivers and the correlation between discharges is very poor even for the adjacent basins (Figure 7). For example, for the Genaldon and Gizeldon rivers, the coefficient of determination R^2 is as low as 0.2 due to differences in the precipitation regimen and a share of ice-melt waters in the flow. The correlation of the time series of annual discharges along the same river is rather high at the adjacent stations with a low input from the tributaries in between. Thus, for the Terek River, R^2 is 0.67 for the Kazbegi and Vladikavkaz stations with a distance of 45 km in between and 0.69 for the Elkhotovo and Kotlyarevskaya stations (35 km). For larger distances (90–140 km) and a significant discharge increase from the tributaries, the correlation between the time series is very poor (R^2 = 0.21–0.24).

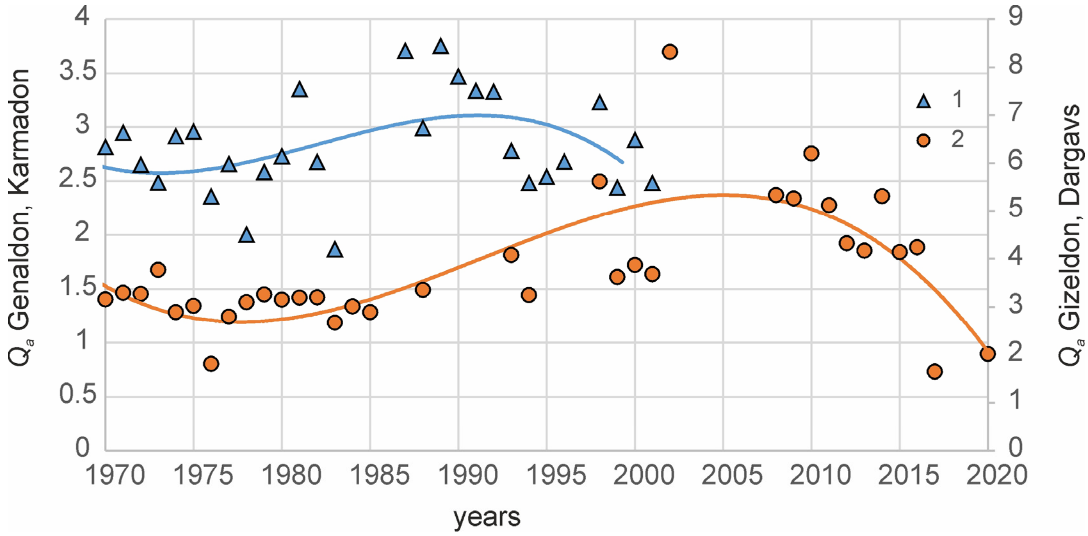

Figure 7. The time series of the annual discharges, Q_a, (m^3 s^{-1}) for Genaldon River, the Karmadon station (1). Gizeldon River, the Dargavs station (2). The polynomial approximation (the lines) shows different temporal changes in water flows at these adjacent basins after 1990.

The discharges at the Kotlyarevskaya station are the sum of the flows from the Terek River and all its tributaries upstream from the Malka River mouth, where the water use for irrigation is insignificant. The polynomial approximation of the time series of the annual discharges (Figure 8) shows a flow decrease during the period 1925–1957 and some increase during the years 1958–2010. There is no correlation between the annual discharges at Kotlyarevskaya and the mean annual air temperatures (R^2 = 0.05) at Vladikavkaz. The correlation is better in terms of the annual precipitation: R^2 = 0.27 for the annual figures and 0.45 for those averaged by polynomial approximation.

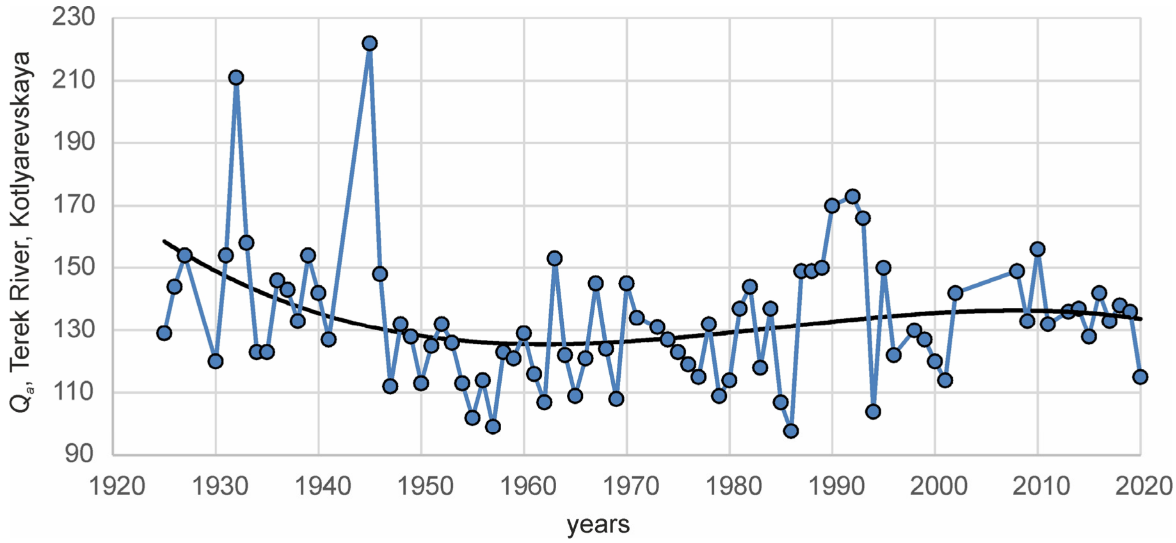

Figure 8. The time series of the annual discharges Q_a (m^3 s^{-1}) for Terek River, the Kotlyarevskaya station with cubic polynomial approximation in black lines.

4.2. The Processes of Incision and Aggradation in the River Channels

The time series ALWS (channel bed deformation) for 18 gauging stations along the Terek River and its tributaries were further analysed using the physiographic regions described in Section 2.1, but moving from the north to the south, from the plains to the mountains.

4.2.1. Tersko–Kuma Lowland

There is one gauging station with discharge measurements on the Terek River in the Tersko–Kuma Lowland: the Mozdok station 359 km from the river mouth. Additional information is available from the low water stage measurements (without discharges) at the Chervlenaya station at 192 km. The basin area, *F*, at this distance slowly increases from 20,600 to 23,100 km^2 and the mean annual discharge, *Q*, at the beginning of the reach is 224 m^3 s^{-1}, suspended sediment transport rate Q_s—300 kg s^{-1}. The longitudinal profile of the water surface is slightly convex with a slope of 0.4–0.6 m km^{-1}. The bedload is mostly sand, with gravel in the upper part of the reach.

The time series of ALWS at the same discharges at the Mozdok station (Figure 9A) shows a rather stable channel in the years 1948–1956, a rapid incision at the rate of 76 mm a^{-1} in the years 1957–1967 and again rapid channel aggradation at the rate of 106 mm a^{-1} in the years 1968–1978. The bed of the Terek River channel stabilised in the years 1979–1988. The discharge measurements were interrupted in 1988 due to natural horizontal deformations when several meanders were abandoned and the channel shortened near the station.

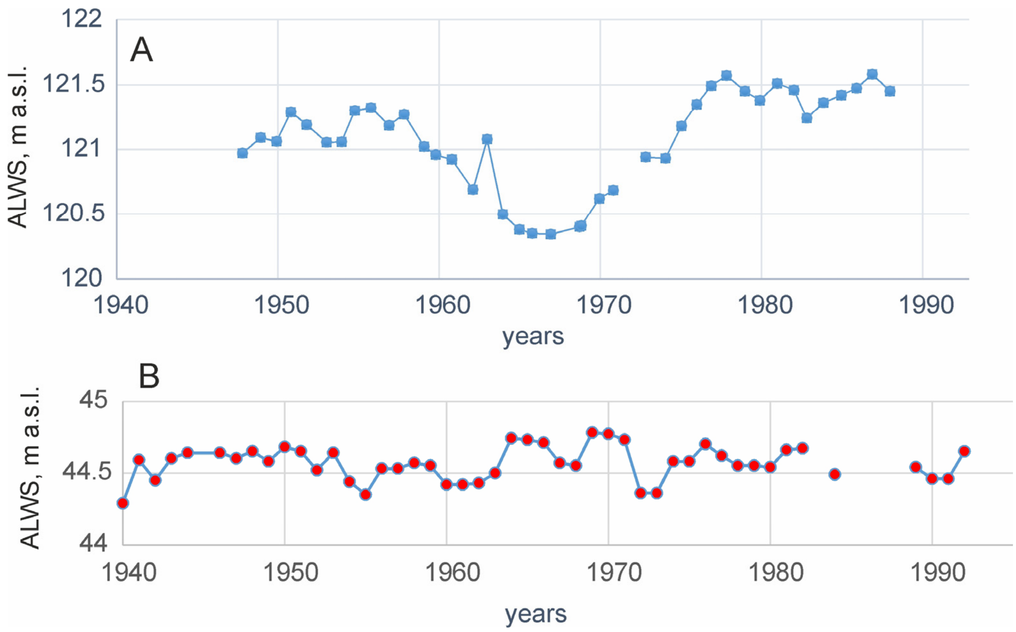

Figure 9. Time series of ALWS at the Mozdok (**A**) and Chervlenaya (**B**) stations. Blue circles or squares here further indicate stages at the same discharge; red ones—minimums of stages for the period of open water.

The rapid incision of the Terek River coincides with the construction of the Tersko–Kuma irrigation canal in 1952–1960 with the dam 18 km upstream from the Mozdok station and of the reservoir with a 14 million m^3 holding capacity, finished in 1959 [34]. This reservoir intercepted nearly all the bedload and partly suspended sediments of the Terek River and was mostly filled by sand as early as during the construction and completely filled by 1963. By then, the filling volume reached 15.8 million m^3, thus exceeding the reservoir capacity. During this period, the Terek River incised to nearly 1 m to cover the deficit of the bed load. After the filled reservoir became a part of the river floodplain and the bed load transport was restored, the volume of incision in the channel was filled approximately at the same rate as it was formed.

The incision–aggradation wave in the years 1957–1978 was not observed at the Chervlenaya station 192 km from the river mouth, where the channel bed was in general stable in the period 1940–1992 (Figure 8B). Therefore, in general, the behaviour of the Terek River channel bed deformations in the Tersko–Kuma Lowland is stable. The well-defined episode of incision–aggradation in the years 1957–1977 in the upper part of this river stretch was caused by human influence and overlapped the natural trend.

4.2.2. The Kabardian Plain

This is only one gauging station, which characterises the channel bed deformations of the Terek River channel on the Kabardian Plain: the Kotlyarevskaya station 437 km from the river mouth (Figure 10). Upstream from this station, the Terek River receives almost all tributaries and the basin area is 8920 km^2. The mean annual discharge is 131 m^3 s^{-1} here. The suspended sediment transport rate—130 kg s^{-1}. The bed load is mostly pebbles with a mean diameter of about 50 mm.

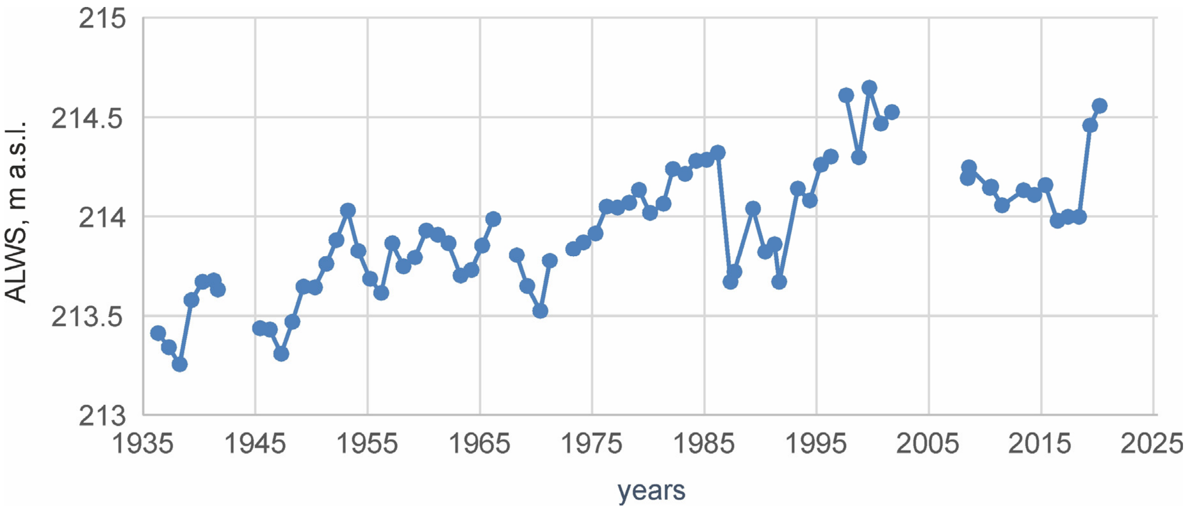

Figure 10. The time series of ALWS at the same discharge at the Kotlyarevskaya station.

The time series of the annual low water stages at the same discharge shows the general channel aggradation 14 mm a^{-1} during the years 1936–2020 with several waves of incision–aggradation. This aggradation trend is assumed to be natural, caused by a general decrease in the river surface slope (see Figure 4). The barrage of the Malo–Kabardian irrigation system about 1 m high crosses the river about 3 km lower than the gauging station and produces a backwater section about 1–1.5 km long. The water level at the gauging station is about 4 m higher than the level on the barrage. The barrage does not interrupt the movement of the bed load as the bars and even islands pass over this barrier (Figure 11).

4.2.3. The Sunzha Ridge

The Terek River crosses the Sunzha Ridge in the antecedent valley of the Elkhotovo Gates for about 6 km. The Elkhotovo gauging station (472 km from the river mouth, F = 6490 km^2, Q = 105.0 m^3 s^{-1}, Q_s = 77 kg s^{-1}) is situated at the lower end of this valley. The water surface profile along the valley is typical for such antecedent valleys: the water slope increases in the lower part of the valley to 4‰ and decreases to 3‰ in the upper part (upstream from the crest of the ridge). The mean diameter of the channel alluvium is 57 mm and the cobble content is 35%.

The time series of ALWS at the same discharges shows the general channel incision at a rate of 32 mm a^{-1} during the years 1936–1983 with several waves of incision–aggradation (Figure 12). The equipment of this station was destroyed in the war and by floods several times and was replaced with the same or similar gauge zero in 1945, 1959 and 1967. The morphology of the valley in the Elkhotovo Gates bears evident signs of channel incision. The channel banks are unstable and protected by heavy constructions; the floodplain is stepped and there are several terraces on the valley slopes [22]. Therefore, despite damage to the gauging station, the high rate of the recent channel incision in the Elkhotovo Gates has been established quite clearly.

Figure 11. Bars and islands passing the barrage of the Malo–Kabardian irrigation system at different dates (yellow numbers). The yellow arrow shows the head of the island, passing the barrage; the red arrow shows the distance the island head moved during the period between images from Google Earth.

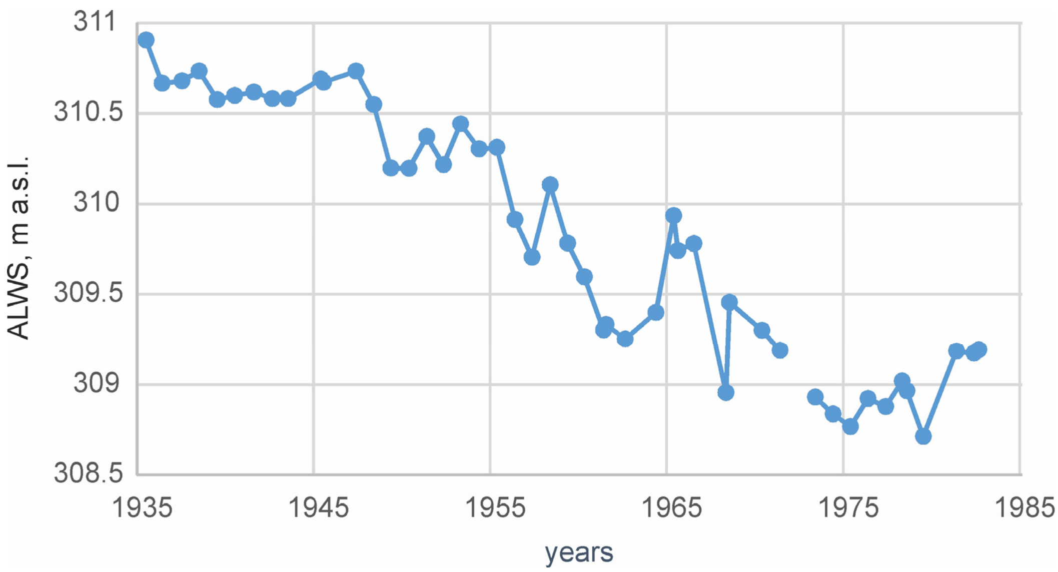

Figure 12. The time series of ALWS for the same discharge at the Elkhotovo station.

4.2.4. The Ossetian Plain

The Ossetian Plain is sloped from the south (altitudes 500–600 m a.s.l.) to the north (altitudes 370–390 m a.s.l.). This inclination is probably the result of the rapid deposition of sediments (mostly cobbles) delivered from the mountains to their piedmont. The gauging stations are mostly situated at this southern piedmont belt at altitudes of 450–600 m a.s.l. The time series of low water stages at the same discharges show a general channel incision for all the rivers that flow to the Terek River upstream from the Elkhotovo Gates (Figure 13). The rates of incision are rather similar and are within the range of 25–28 mm a^{-1} for the periods of measurements of up to 85 years. Presumably, these tributaries of the Terek River are under the influence of rapid river incision in the Elkhotovo Gates, with regressive erosion being the main recent process.

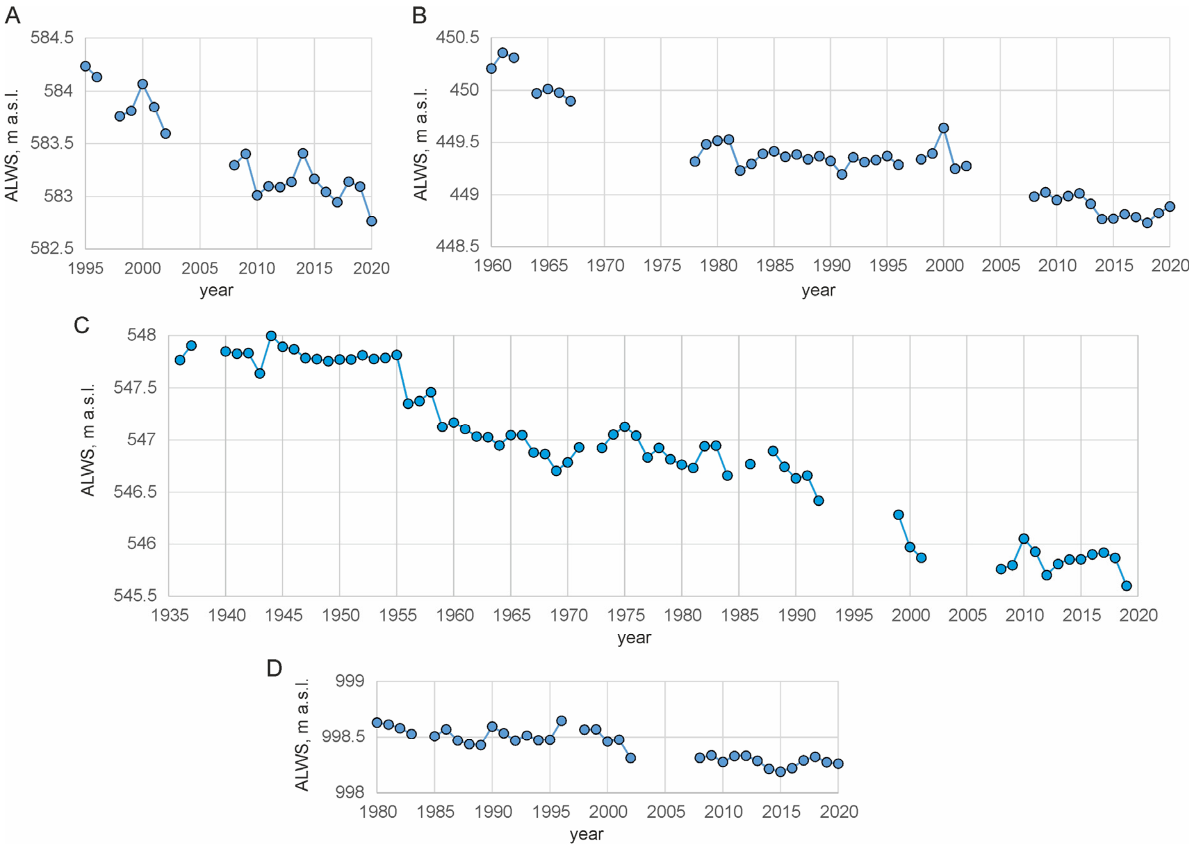

Figure 13. The time series of ALWS for the same discharge at the Kora Ursdon (Belaya River, (**A**)), Michurino (Figagdon River, (**B**)), Olginskoye (Kambileyevka River, (**C**)) and Tarskoye (Terchek River, (**D**) stations. For positions of the stations, see Table 1 and Figure 3.

Two gauging stations from this area differ from the above described: Vladikavkaz on the main river (Terek) and Khaznidon on the Urukh River. The time series of ALWS at the same discharges in Vladikavkaz (Figure 14) shows aggradation in the years 1936–1950, incision in the years 1950–1965 and the subsequent stabilisation of the channel until the present. This channel bed behaviour is significantly influenced by humans. There were several water mills downstream from the gauge in the 1930s, which produced backwater effects and caused the deposition of sediments. After the mills were destroyed, these deposited sediments (cobbles and pebbles) were moved down the river and the channel bed was lowered at the gauging station section. Channel stabilisation was achieved later by the construction of a series of submerged weirs on the river in Vladikavkaz city. These submerged weirs prevented the channel from incision, which is a natural process in the sections of the river described above and, with a high degree of probability, is a natural process for the entire Terek River stretch from Elkhotovo to Vladikavkaz.

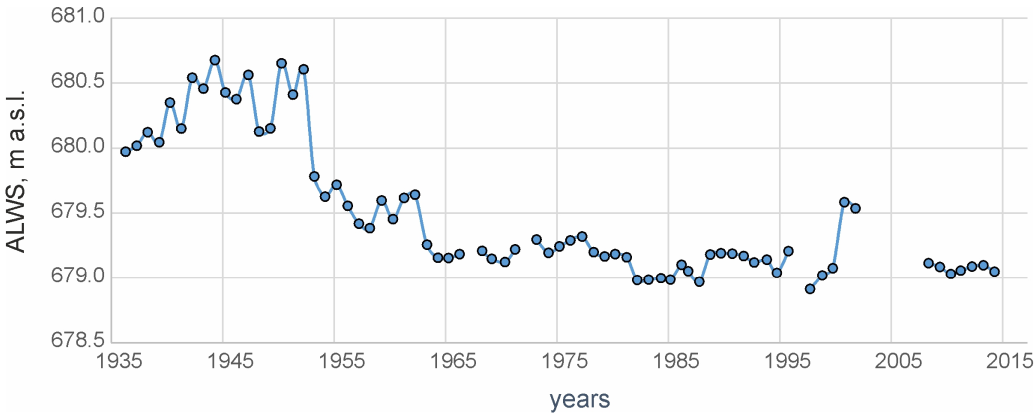

Figure 14. The time series of ALWS for the same discharge at the Vladikavkaz station (Terek River).

The channel bed deformation of the Urukh River at the Khaznidon gauging station is of a completely different type. This river flows into the Terek River downstream from Elkhotovo Gates and, therefore, is not influenced by regressive erosion. There is no visible overall trend in the ALWS at the same discharges at this gauge for the years 1965–2020 (Figure 15). The periods of aggradation take turns with periods of incision so that three or four waves passed through this section over the course of 55 years. At least two periods of aggradation coincide with a series of large debris flows from the slopes, some with more than 300,000 m^3 of deposits delivered to the river [35]. At the periods with more stable mountain slopes, sediments (cobbles and pebbles) moved down the river and the channel bed lowered.

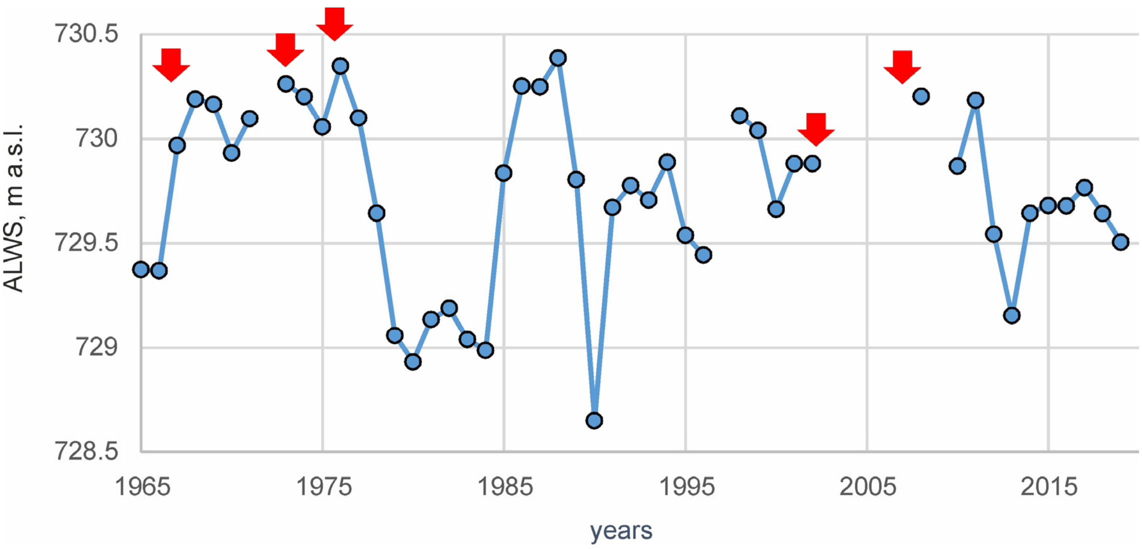

Figure 15. Time series of ALWS for the same discharge at the Khaznidon station (the Urukh River). Red arrows here and further show the years with debris flows with volumes greater than 10,000 m^3.

4.2.5. The Caucasus Mountains

The time series of ALWS at the same discharges from the gauging stations in the mountains are all different (Figure 16) but show processes similar to the one described above for the Urukh River. There is no overall trend for aggradation or incision at these river sections; instead, the periods of aggradation and incision take turns there. The durations of these periods are different, presumably depending on the phases of stability or instability of mountain slopes at a given river basin.

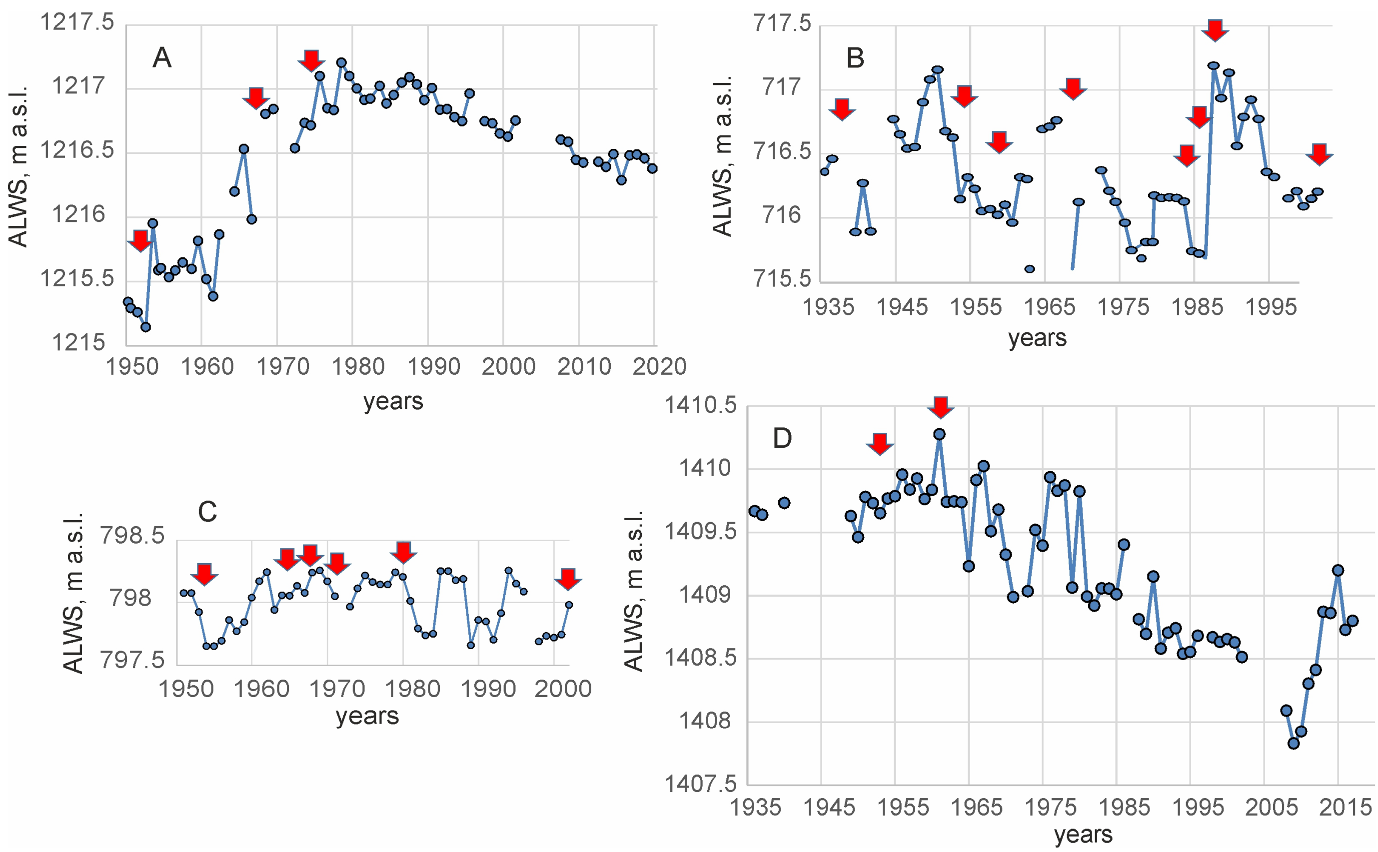

Figure 16. The time series of ALWS for the same discharge at the Buron (the Zeyadon River, (**A**)), Tamisk (the Ardon River, (**B**)), Tagardon (the Fiagdon River, (**C**)) and Dargavs (the Gizeldon River, (**D**)) stations.

At the Zeyadon River, a tributary of the Ardon River, a series of debris flows occurred in the years 1939–1975. Some of them were very severe with a volume of about 600,000 m^3. River channel aggradation about 2 m thick was observed in ALWS at the Buron gauging station for this period (Figure 16A). The mountain slopes were stable here during the following period, at least until the year 2015 [35], despite high activity of debris flows in neighbouring river basins. During this period of slope stability, the sediments (boulders and cobbles) that were deposited earlier moved into the Ardon River and the bed of the Zeyadon River lowered.

The basin of the Ardon River (including the Zeyadon River) is one of the most vulnerable to debris flow activity [35]. There are 58 tributary basins where large debris flows with volumes over 10,000 m^3 form, i.e., one debris flow basin per ~20 km^2. During the period 1936–2015, a series of large debris flows occurred there 25 times (i.e., on average once every three years) and smaller ones occurred several times a year. The resulting channel bed deformation at the Tamisk gauging station was wavelike: at least 5 aggradation–incision waves with durations of 8–20 years each were observed in ALWS within this 79-year period (Figure 16B). The amplitude of these waves reached 1.5 m; these channel bed deformations indicate a significant amount of bedload transport along the river, mostly boulders.

The mountain slopes at the Fiagdon River basin are more stable. There are 14 main locations where large debris flows with volumes of more than 10,000 m^3 initiate. All these locations are upstream from the Tagardon gauging station with a contributing basin area of 410 km^2, i.e., one debris flow source per ~30 km^2. The series of debris flows occurred here only seven times in the years 1936–2015, five times before the year 1980 and two times after the year 2002 [35]. As a result, there was mostly aggradation of the river channel bed at the Tagardon gauging station before the year 1980 and a few waves of aggradation–incision with amplitudes of about 0.5 m during the period of slopes stability in 1980–2002

(Figure 16C). The gauging station equipment was completely destroyed by the extremal flood in 2002 and the measurements there stopped.

There are five main locations of initiation of large debris flows with volumes of more than 10,000 m^3 in the upper part of the Gizeldon River basin, i.e., one debris flow basin for an area of ~25 km^2. The debris flows were reported only for the years 1953 and 1961 [35]. Slow aggradation in the river channel was registered in the time series of ALWS at the same discharges for the period before the year 1961 at the Dargavs station (Figure 16D) and the channel bed lowered by 2 m during the subsequent 50 years. A new stage of aggradation in the channel began in 2002 after powerful summer floods that occurred throughout the entire territory of the North Caucasus.

In the upper part of the Genaldon River basin, there are also 5 main locations of large debris flow initiation with volumes of over 10,000 m^3, i.e., one debris flow basin per ~20 km^2 [35]. This is a rather high density of small basins with unstable slopes. Three episodes of debris flows were reported for the period between the years 1936–1967. However, the main processes of sediments delivered to the channel were the collapses of the Kolka glacier, situated at the headwaters of Genaldon River. Such collapses were described in 1877 and 1902 [36]. The collapse of 1969 was well investigated [37]. The collapse of 2002, which caused human deaths, raised a lot of publications and hypotheses [38–41].

The time series of ALWS at the same discharges are available from three gauging stations, sequentially opened and closed: Tmenikau 1936–1956, old Karmadon 1962–2002 and new Karmadon 2004 until present. The ALWS registered at Tmenikau and during the first 20 years at the Karmadon station are similar: the waves of the channel aggradation and lowering in a period of 10–12 years and an amplitude of about 0.5 m (Figure 17A,B). The collapse of the Kolka glacier in the years 1969–1970 caused no visible channel bed deformations. The ice from the glacial cirque passed through the valley of the Genaldon River and its front stopped about 14 km upstream of the Karmadon gauging station. The volume of the displaced ice was about 80 million m^3 but the discharge measurements showed no changes in the hydrological regime of the Genaldon River. Presumably, the impact of this collapse began to manifest itself in channel bed deformations only after the year 1984, when the channel bed altitude sharply increased about 1 m in 2 years and this aggradation continued more slowly (2 m in 16 years) until the year 2002.

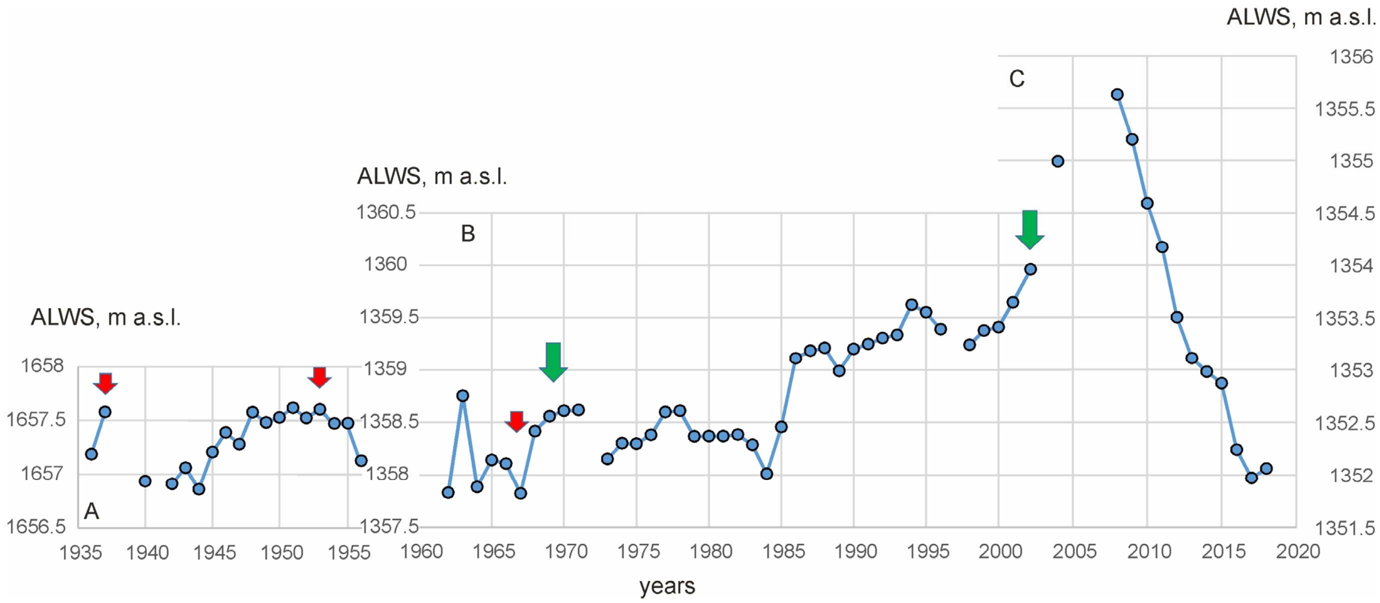

Figure 17. The time series of ALWS for the same discharge at the Tmenikau (**A**), Karmadon old (**B**) and Karmadon new (**C**) stations at the Genaldon River. Green arrows show the Kolka glacier collapses in the years 1969–1970 and 2002.

The collapse of the Kolka glacier in September 2002 was much more severe and caused the death of a large number of people. The cirque of this glacier was nearly emptied, as about 100–140 million m^3 of ice and debris was ejected into the Genaldon River valley to a distance of 18 km at a rate of 107–115 m s^{-1} [41]. This ice–stone mass occupied about 5 km along the valley; its front stopped at the entrance to the Karmadon Gorge and its far end was located approximately at the site of the destroyed gauging station. The station was reopened in 2006 in approximately the same place (with the same contributing basin area of 70 km^2 but with a lower zero of the station). Some measurements were taken there as early as the year 2004; official data are available from the year 2008. In the period 2008–2018, the bed of the Genaldon River lowered by 3.5 m, presumably due to erosion and melting of the blocking ice–debris mass (Figure 17C).

Part of the debris from the Kolka glacier collapse was moved by the water flow along the Karmadon Gorge and was deposited there. A rather small amount of sediments reached the piedmont at the Ossetian Plain. A new gauging station, Gizel, was opened here promptly in October 2002 to monitor discharges in the Gizeldon River as there was a possibility of sharp flash floods from the lakes formed by glacier dams in the Genaldon River valley. Fortunately, these lakes emptied slowly, meaning that the measurements at the Gizel station did not show any significant changes in the hydrologic regime of the river, even after the glacier collapse in 1969. In the years 2002–2004, the Gizeldon River channel was filled here by pebbles, cobbles and boulders to more than 1 m. From the year 2008 (the beginning of data publication) to 2020, the bed of the channel was lowered there by about 1 m (Figure 18).

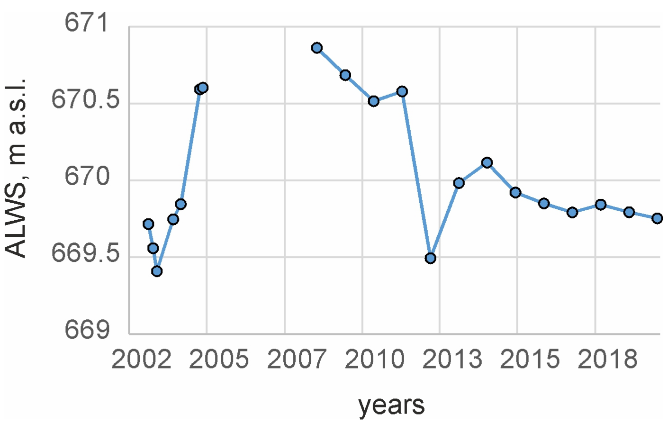

Figure 18. The time series of ALWS for the same discharge at the Gizel station (the Gizeldon River).

A general type of channel bed deformations in the Terek River basin in the North Caucasus Mountains is the alternating aggradations and incisions in periods of 8–20 years and amplitudes of 0.5–2 m and during catastrophic events more than 3 m. The aggradations were caused, usually, by debris flows from unstable slopes or, as in the Genaldon River valley, by glacier collapses. The incisions followed these aggradation events during the periods of mountain slope stability when the coarse alluvium moved down the river. No visible overall trends of aggradation or incision were recorded for a 50–85 year period of the measurements at the gauging stations in the mountains.

4.2.6. The Kazbegi Gauging Station

The only gauging station in the mountains with a distinct incision trend of ALWS was situated at the Terek River high mountain section affected by tectonic uplift and volcanic explosions. The main volcano, Kazbek, 5033 m high and several smaller volcanoes repeatedly erupted during the time of the Caucasus Mountains formation. The last series of eruptions, when the flows of andesitic magma again blocked the valley of the Terek River, dates back to 185–200 ka BP [42]. The river cut through these andesitic ridges, forming antecedent valleys. The slope changes along the longitudinal profile of the flow surface are typical for this type of valley: the slope increases at the lower edge of the valley and decreases at the upper edge. The ALWS curve at the Kazbegi station, which was situated in the central part of one of the antecedent valleys, showed a rapid incision of the river at a rate of 37–38 mm a^{-1} for the years 1945–1986 (Figure 19). Later, the station was closed. The potential for river incision is still high in this section.

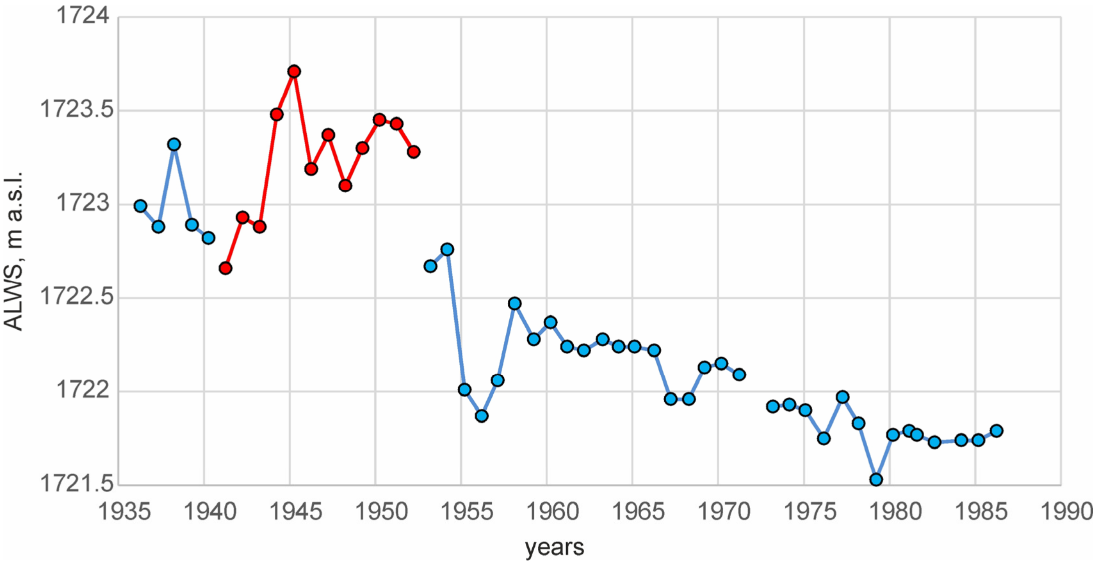

Figure 19. The time series of ALWS for the same discharge (blue circles) at the Kazbegi station (the Terek River). Red circles show the minimum stages for the period of open water.

4.3. General Pattern of the Channel Bed Deformations in the Terek River Basin

In the Terek River basin, according to hydrological measurements, three main types of natural channel bed deformation are distinguished: (1) channel aggradation; (2) channel incision, (3) the passage of long waves of bed load transport in the absence of definite long–term trends of aggradation or incision; (4) incision into andesite magma ridges and (5) channel stability (Figure 20).

On the Tersko–Kuma Lowland on the Terek River between its confluences with the Malka and Sunzha rivers (390–165 km), the natural channel was in general stable and the resulting trend was negligible. Small waves of incision and aggradation were observed at the Mozdok and Chervlenaya stations and reflected the local movement of alluvial bars. The influence of human activity is well expressed in this section of the river.

On the Kabardian Plain, the aggradation of the Terek River channel was observed upstream from the Malka River mouth. If we assume that the rate of the natural sediment deposition in this 70-km-ling stretch of the river was 14 mm a^{-1}, as recorded at the Kotlyarevskaya station, the average annual volume of deposits in the channel was 0.25 million m^3 of sediment. These deposits are mostly coarse gravel (pebbles) and cobbles.

In the antecedent valley called the Elkhotovo Gates, the intensive incision at a rate of 32 mm a^{-1} occurs. It regressively propagates along the main river and all its tributaries in the sloped Ossetian Plain up to the Caucasus piedmonts. The rates of incision are 25–28 mm a^{-1} in the mid–sections of the channels and ~10 mm a^{-1} at the most upstream station (Tarskoye on the Terchek River). The decrease in the incision rate along the channels is close to linear, with a mean rate of 25 mm a^{-1}. The annual volume of overall erosion at the sloped Ossetian Plain is ~0.65 million m^3 in the natural conditions and ~0.4 million m^3 when taking into account the channel protection constructions. The channel bed alluvium consists of pebbles and cobbles.

The bed deformations in the channels in the Terek River basin in the Caucasus Mountains are wavelike. The aggradation was caused by debris flows from unstable slopes or by glacier collapses, while the incisions occurred during periods of mountain slope stability.

These waves of aggradation and incision reflect the movement of the coarse alluvium (cobbles and boulders) down the river. No visible overall trends of aggradation or incision were registered for a 50–85 year period. Presumably, as there are no trends in the channel bed deformations, all coarse material delivered from the slopes and glaciers to the channels was eventually transported by river flows to the piedmonts.

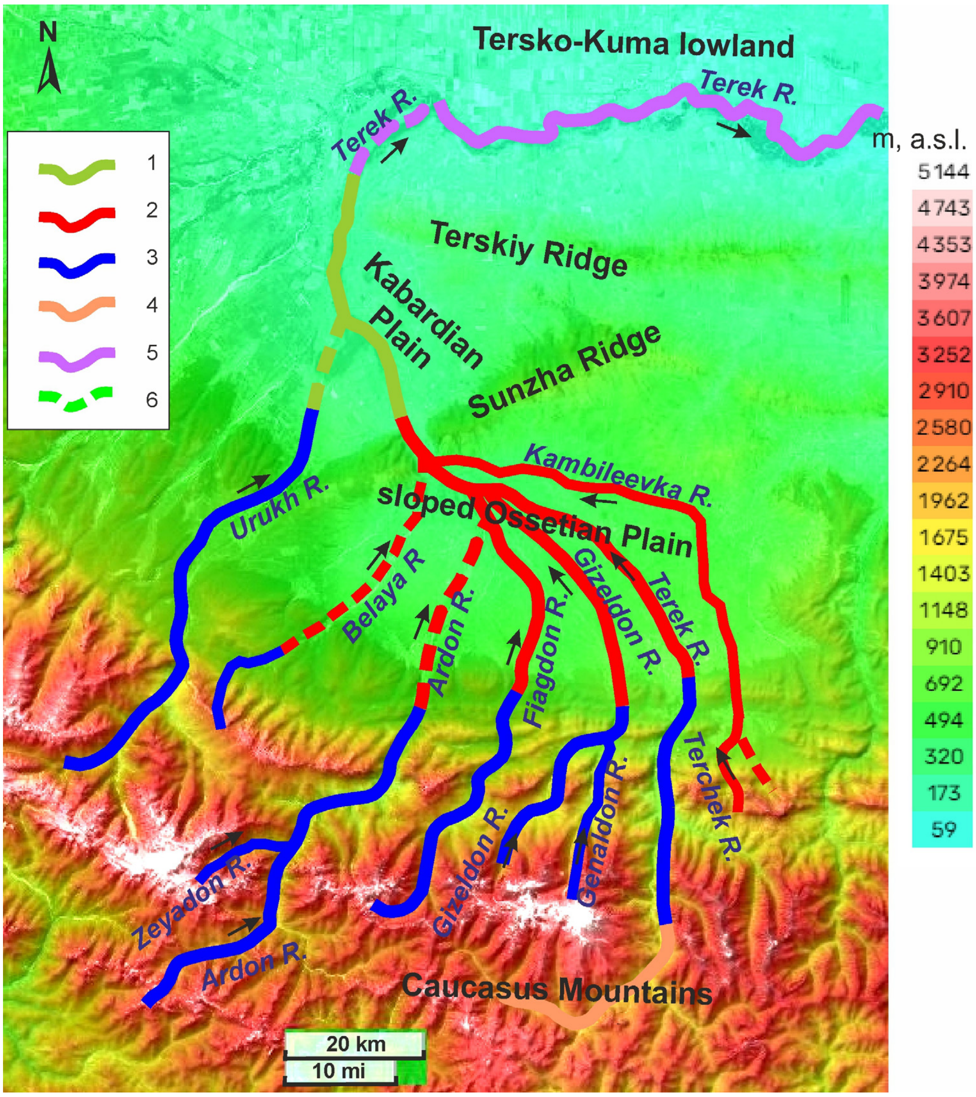

Figure 20. The main types of the long-term processes in river channels in the Terek River basin, estimated from hydrological measurements: (1) aggradation; (2) incision; (3) overall stability with the aggradation–incision waves; (4) incision into andesite magma ridges; (5) overall stability and (6) a supposed type. The cartographic background is from free topographic maps available at https://en-us.topographic-map.com (accessed on 17 June 2023).

There is insufficient information for estimating the volume of this moving coarse bedload (cobbles and boulders). The volumes are estimated only for the largest debris flows [35] and with great errors [43]. The main part of these debris flows in terms of volume are fine particles that were transported into the Terek River delta as suspended loads shortly after the debris flow event.

The transport rate of bedload in the form of waves can be calculated as the product of wave amplitude and wave celerity (with some shape factor). It is possible to make an approximate estimate of the celerity of the bedload wave after the event of the Kolka glacier collapse in 1969. The glacier lobe stopped near the Upper Karmadon mineral water wells in

1969–1970 and the sediment wave with an amplitude of about 1 m and a mean width of ~10 m reached the Karmadon gauging station situated 14 km down the river in 1984. Therefore, the mean annual bed load transport rate of the coarse material (boulders and cobbles) was ~10,000 m^3 in the river with a mean annual discharge of 2.6 $m^3\ s^{-1}$ for this period.

The incision into the magmatic ridge, which blocks a river, is rather typical for the mountains [44], but in the Terek River basin, such a situation is observed only in the volcanic field of Kazbek. There were several magma flows of different ages forming dams in the Terek River valley in various places of the 25-km-long section upstream from the Dariali Gorge. The rate of the river incision was measured only at one point—the Kazbegi gauging station, which was situated on the Chkheri magma flow [42]. This tongue was formed in the Middle Pleistocene, but the rate of the river incision is still very high: 37–38 mm a^{-1}.

5. Discussion

There are three main problems to discuss: (1) the influence of climate change on the long-term deformations of the river channels in the Terek River basin; (2) the interaction of tectonic and fluvial processes; and (3) human impact on the fluvial processes in the Terek River basin.

5.1. The Influence of Climatic Factors

As was shown in Section 4.1.3, the discharge at the Kotlyarevskaya station, which is a sum of all water flow from the mountain part of the Terek River basin upstream from the Malka River mouth, is not directly correlated with the air temperature and its correlation with the precipitation at the Vladikavkaz station is low. There is no information on the degree of such correlation for each particular river basin. However, the regimen of channel bed deformations in the mountains, described in Section 4.2.5, shows that the main process there is the transport of sediments from slopes by debris flows. The volumes of this transport are estimated with large errors [43]; therefore, the number of debris flows per year from [35] will be used instead as the characteristic of debris flow intensity (Figure 21A). The relationship between these numbers and the precipitation (Figure 21B) is expressed as the upper envelope of the scatter. Therefore, it shows the influence of two main factors, which control the intensity of debris flows: the amount of precipitation during the summer and the duration of the period of slope debris preparation. The description of debris flow formation is beyond the content of the current article; see, for example, [45]. The main conclusion is that climate-related debris flows are the main factor of the vertical river channel deformation in the mountainous part of the Terek River basin. The impact of debris flows on vertical deformation completely outweighs the influence of all other processes, including changes in discharge over time or tectonic movements.

Climate change is well expressed in the increase in air temperature, especially in the last 30 years, but not clearly expressed in other climatic characteristics, such as precipitation and water runoff. The flood of the year 2002 was severe and ended with the Kolka Glacier catastrophe. However, the flood of 1932 was more powerful and the flood of 1917 has not yet been surpassed. Therefore, the temporal changes in the altitudes of the river channels in the plains and foothills are not directly influenced by the climate.

5.2. The Influence of Geologic and Geomorphologic Factors

As was mentioned in the introduction, bed deformations in river channels are usually studied using geological and geomorphological methods. The rates of such deformations are estimated using the relative heights of dated terraces or the thicknesses of alluvium accumulations, usually averaged over periods of thousands of years or more. Hydrological measurements of discharges and water stages at gauging stations make it possible to estimate the recent (centennial and decadal) magnitudes and rates of bed deformations in river channels with high accuracy. It is interesting to compare the results of these two approaches in the example of the Terek River basin in the tectonically active North Caucasus, at least for the large physiographic regions (Table 2).

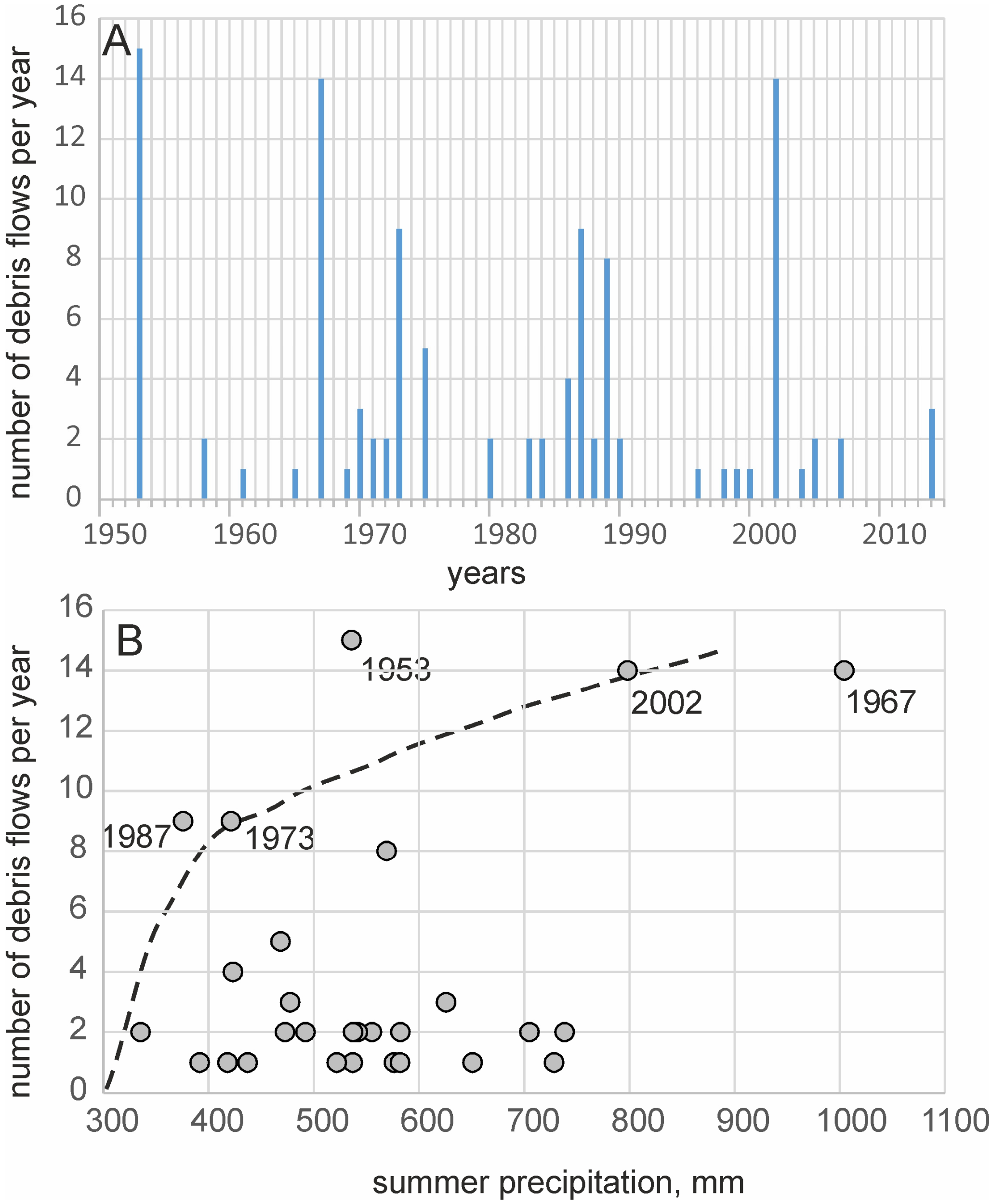

Figure 21. The number per year of debris flows in the mountains of the Terek River basin ((**A**), after [35]) and the relationship with the precipitation during the summer (May–September) at Vladikavkaz (**B**).

The Tersko–Kuma Lowland is situated within a deep synclinorium with 1.5-km-thick deposits younger than the Akchagylian time. The geological data show that the mean rate of subsidence and deposit accumulation is ~0.4 mm a^{-1}. The hydrological data show the overall stability of the Terek River channel bed altitudes with small waves of aggradation and incision.

The thickness of sediments younger than Akchagylian on the Kabardian Plain is up to 1.5 km, and the rate of subsidence there is ~0.4 mm a^{-1}. The time series of ALWS at the same discharges shows the general channel aggradation by 14 mm a^{-1} during the last 85 years. The difference by one or two orders of magnitude between the estimates with geological and hydrological methods clearly indicates different causes of surface altitude changes: the tectonics in the first case and the sediment budget in the second. The trend for sediment deposition intensifies as the slope decreases with time. Over the past 85 years, the river bottom has risen by the aggradation by 1.0 m in the area of the Kotlyarevskaya station and has sunk by erosion by 2.5 m 35 km upstream in Elkhotovo.

Table 2. The correlation between the processes of incision and aggradation in the river channels of the Terek River basin in the recent past and tectonic movements in this territory during the last 3.4 million years.

The Physiographic Region	Type and the Rate of Channel Bed Deformation	Type and the Rate of Tectonic Movements
Tersko-Kuma Lowland	Overall channel natural stability with significant human impact lowered the Tersko–Kuma irrigation system dam: incision at a rate of 76 mm a^{-1} in the years 1957–1967 and again channel bed aggradation at a rate of 110 mm a^{-1} in the years 1968–1978	The subsidence of the Terek fore deep with a mean rate of ~0.4 mm a^{-1} to the north of Terskiy anticline
Kabardian Plain	Channel bed natural aggradation at a rate of 14 mm a^{-1}	The subsidence of the Terek fore deep with a mean rate of ~0.4 mm a^{-1} in between the Terskiy and Sunza anticlines (Alkhanchurt syncline).
Sundza Ridge	General channel incision at a rate of 32 mm a^{-1}	The uplift of the Sunza anticline at a rate of 0.3 mm a^{-1}
Ossetian Plain	General incision in the river channels at a rate of 10–25 mm a^{-1}. Locally, the incision was artificially stopped with a series of submerged weirs	The subsidence of the Terek fore deep with a mean rate of ~0.4 mm a^{-1} to the south of Sunza anticline (Ossetian basin)
The ridges and basins of the North Caucasus Mountains	Wavelike channel bed deformations. The aggradation was caused by debris flows, while the incisions occurred during periods of mountain slope stability. No visible overall trends in aggradation or incision were registered for a 50–85 year period.	Uplift at a rate of 0.7–0.9 mm a^{-1} of the tectonic blocks, divided by the faults
The upper part of the Darialy Gorge	The incision of the Terek River at a rate of 37 mm a^{-1} into magmatic ridge, which blocked the river in the Middle Pleistocene	The uplift of Kazbek Mountain region at a rate of 0.7 mm a^{-1}

The altitudes of the Middle Pleistocene terraces on the slopes of the Sunzha Ridge [24] make it possible to estimate the long-term mean rate of the river incision of 0.2–0.4 mm a^{-1}, which is close to the rate of tectonic uplift. The mean rate of Terek River incision for 50 years at the Elkhotovo Gates is 32 mm a^{-1}, i.e., 100 times higher. The cause of this high rate of river incision is not clear. The flow surface slope and the size of the channel alluvium increase in the Elkhotovo Gates, showing an increase in flow velocity and the potential of the river to incise here. However, this increase in flow velocity is not high enough to explain the 100-times increase in the incision rates relative to the long-term mean. Presumably, the longer history of relief evolution of the Sunzha Ridge can help to answer the question. This is a case when a relatively short hydrological fluvial archive should be continued with the use of longer fluvial archives (alluvial sediment sequences and fluvial relief).

In the first three physiographic regions, estimates of the general direction of changes in the surface altitudes (but not their magnitudes) using geological and hydrological methods are consistent with each other: sedimentation occurs in sinking regions and incisions in the uplifting ones. However, this consistency is not true for the Ossetian Plain. Since the thickness of deposits younger than the Akchagylian on the plain reaches 1.5 km, the average rate of subsidence here is estimated at ~0.4 mm a^{-1}. Nevertheless, the rivers, which cross this plain and flow into the Terek River upstream from the Elkhotovo Gates, mostly incise at rates of 10–25 mm a^{-1}. We assume that this incision is regressive and caused by the Terek River incision in the Elkhotovo Gates, as the rivers that flow into the Terek River lower than the Elkhotovo Gates (such as the Urukh River) do not incise. It is more difficult to explain the reason for the rapid incision of the Terek in the antecedent valley of the Elkhotovo Gates itself. Presumably, there was a long stage when the incision stopped here due to some blockages that caused backwater and deposition in the channels on the Ossetian Plain. The modern incision may be a reaction of the river network to the destruction of this obstacle.

The geological and geomorphological data show that the mean rate of tectonic uplift of the Northern Caucasus to the height of 2.5–3 km was about 0.7–0.9 mm a^{-1}. The Terek River and its tributaries are incised for 2.0–3.0 km in the middle parts of their valleys. As was described in Section 5.1, in the last 50–85 years this tectonic uplift was not reflected in the fluvial processes in the majority of the rivers. Instead of the expected incision, the main process here is the transport of sediments delivered from unstable slopes as debris flows or glaciers collapse.

The only area where tectonics has clearly affected river processes is the region of the Kazbek Mountain. A large number of magmatic flows from volcanoes crossed the Terek valley in several places and formed andesite dams, into which the river incised, forming gorges of various sizes. The formation of these dams, which caused a temporary high-speed incision, slowed down the general deepening of the river valley: there is a well-defined step on the longitudinal profile of the Terek River with relatively low slopes in the fields of magma deposition and high slopes downstream (Darialy Gorge).

Magma flows are not the only reason for this river valley morphology. Debris flows often pass from the slopes of the Kazbek Mountain; some of them carry a large amount of coarse sediments into the valley of the Terek River, which can block the channel. A quite recent example (in May 2014) is when ice and debris flow from one of the glaciers on the Kazbek (called Devdorak) blocked the Terek River channel with a mixture of ice and stones with a volume of 800,000 m^3 [46].

5.3. The Human Impact

The main constructions in the river channels at the Terek River basin are the dams with reservoirs, the barrages for water output for irrigation and hydropower purposes and different types of channel bed and bank protection constructions.

The dams with reservoirs change the natural transport of channel-forming sediments and, therefore, the sediment budget in the channel downstream from the dam. There are two such dams in the Terek River basin: on the Gizeldon River 8 km downstream from the Dargavs gauging station and on the Terek River upstream from the Mozdok gauging station. The first reservoir constructed in 1932 was completely filled with 11.8 million tons of sediments in five years [47]. The bed deformations in the river channel associated with the construction and filling of this reservoir have not been investigated. The influence of the second reservoir was described in Section 4.2.2. The nearly complete interception of the bedload caused the positive sediment budget downstream from the dam of the Tersko–Kuma irrigation system and the river channel incision by about 1 m for 10 years with a corresponding decrease in the channel slope. During the next 10 years, when the bedload transport was restored, the incision changed to aggradation but the local river flow capacity decreased with the slope decrease and the sediment budget became negative. All these changes in the sediment budget were of a local nature and were not observed approximately 160 km downstream from the Mozdok gauging station or possibly even much closer to the station.

The barrages constructed for irrigation and hydropower purposes are numerous and a lot of them were abandoned. Even the largest of them, such as the barrage of the Malo–Kabardian irrigation system, are less than 1 m high and do not interrupt the bedload transport, as was shown in Section 4.2.2. Usually, the regional hydrologic department shift or close those gauging stations, where measurements come under the influence of such barrages.

The channel bed and bank protection concrete weirs were constructed in the main river channel between Vladikavkaz and Elkhotovo to minimize the effect of the channel bed incision along this stretch. The constructions of this type nearly completely stopped the natural process of channel incision.

5.4. The Possibilities of Stage–Discharge Method Application

The stage–discharge method of estimation of the channel bed deformation is simple and effective. The information about the water stages and discharges at the gauging stations is available from the national [25,28] and international [48] databases for the broad range of natural environments, from the plains to high mountains, with different climates and geology and different levels of human impact. The stage–discharge method so far has not been broadly used in international research. The example of the Terek River basin shows the possibility of regional investigations of channel bed deformations with intra-regional correlations of the processes and factors. The extension of such studies to other regions may provide an opportunity for interregional correlations of the characteristics of fluvial processes, based on a unified stage–discharge method.

6. Conclusions

The recent (in the last 50–85 years) channel bed deformations in the Terek River and its tributaries within the North Caucasus were estimated from the time series of low water stages for the same discharges—from fluvial archives from 18 gauging stations.

The stability of the Terek River channel was observed within the tectonically sinking Tersko–Kuma Lowland and channel aggradation at rates of up to 14 mm a^{-1} occur on the sinking Kabardinian Plain. A rapid (~32 mm a^{-1}) incision of the Terek River channel occurs along the antecedent valley in the raising Sunzha Ridge. This incision causes regressive erosion in the main river and its tributaries and their incision at a rate of ca. 25 mm a^{-1} on the Ossetian Plain despite the tectonic sinking of this region.

The main process in the uplifting mountains of the North Caucasus is the transport of sediments delivered from unstable slopes as debris flows or glaciers collapse. Here in the river channels, aggradation alternates with incision without a visible overall temporal trend.

Climate change, well pronounced in the increase in air temperatures, especially during the last 30 years, is not registered in other climatic characteristics, such as precipitation and water flow.

Slope stability most obviously depends on climatic conditions. The amount of precipitation during the summer is one of the main factors that control the frequency of debris flows. Debris flows are the main cause of vertical river channel deformation in the mountainous part of the Terek River basin. All other processes, including temporal changes of discharge or an influence of the tectonic movements, are completely outweighed by the impact of debris flows.

The rates of the modern deformations of the river channel beds are from 10 times higher at the Tersko–Kuma Lowland to 100 times higher at the Sunzha Ridge than the rates of tectonic uplift or subsidence. This means that, despite the North Caucasus being one of the most tectonically active territories, tectonics does not influence the recent fluvial processes directly. Tectonics cause changes in river channel slopes, which in turn cause changes in the bed load transport budget and channel bed deformations. The best example of this is the incision of the Terek River channel in the volcanic field of Kazbek (Darialy Gorge).

The current 100-fold increase in the incision velocity of the Terek River channel at the crossing of the rising Sunzha Ridge relative to the long-term average velocity cannot be explained based on the data for the last century. This is an example when a relatively short hydrological archive is insufficient for the reconstruction and it will have to be extended with longer fluvial archives, such as alluvial sediment sequences and fluvial relief, as described in the introduction.

The constructions in the river channels in the Terek River basin can either cause or reduce channel bed deformations. Most of the constructions, such as dams and barrages, can induce rapid deformations in the river channels but they have a local spatial and temporal effect.

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